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Meteorological aspects of winter upward lightning from an instrumented tower in the Pyrenees

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***Abstract*— A case study of winter upward lightning is analysed. In particular, the study focuses on the meteorological aspects that favoured the triggering of upward lightning by an instrumented tower in the eastern Pyrenees. Starting from the lightning currents measured at the Eagle Nest Tower, and taking advantage of other singular meteorological instruments deployed in the region, the obtained results showed how a small winter thunderstorm can create the necessary conditions for the inception of self-initiated upward lightning from a small tower. Beyond the particularities of the present case study, the results provide new evidence on the necessity to include upward flashes in risk assessment.**

***Keywords*— upward lightning, winter lightning, instrumented tower, current waveforms, meteorological conditions for lightning triggering, lightning risk assessment**

I. Introduction

Small structures of limited height (< 100 m) may be affected mainly by downward strikes. Contrarily, tall towers under thunderclouds, exposed to strong local electric fields, are prone to initiate upward lightning (e.g. [1]). However, upward lightning has also been reported on small towers located on mountain tops (e.g. [2]). The shape of the mountain appears to be adding a field enhancement factor, resulting in an "effective height" that is considerably larger than the physical height of the tower [3-4].

Winter thunderstorms can present favourable conditions for the initiation of upward lightning flashes from these "effective" tall structures (e.g. [5-7]). Despite the modest occurrence of winter lightning, these storms can produce very energetic lightning and a large amount of damage (e.g. [8]). Although the best-known winter lightning activity is in Japan, other areas such as the Mediterranean and the US east coast have been found to be active in winter as well [9-10].

When the electric field over a tall structure intensifies, an upward leader may propagate from the tip of the structure: An initial continuous current (ICC) flows along this channel typically for tens to several hundred milliseconds. The ICC may be followed by one or more cloud-to-ground (CG) return strokes, which are similar to subsequent return strokes in natural downward lightning [11].

Upward lightning (UL) from tall objects can be one of two types: self-initiated or lightning-triggered. When the leader inception is due to locally strong electric fields but without any preceding lightning, the upward is termed self-initiated (SIUL). When the upward is triggered by prior lightning discharges in the vicinity, is termed lightning-triggered (LTUL). LTUL can be triggered by nearby +CG return strokes or by intra-cloud (IC) lightning horizontally propagating overhead in the vicinity of the tower (e.g. [12-15]).

The knowledge of the lightning current waveforms is of primary interest for the analysis of lightning interaction with electrical power systems and for the design of relevant protections. Given the low probability of measuring a direct current on a random point, instrumenting elevated towers, more prone to lightning strikes, provides a good way of measuring lightning currents. This way, lightning current waveforms may be obtained by direct measurements using instrumented towers (e.g. [1-2], [16-17]).

In addition, it is also important to increase our knowledge of the meteorological environment favouring the inception of lightning from towers and other tall man-made structures like wind turbines. The present work analyses some of the meteorological aspects that favoured the self-triggering of upward lightning from an instrumented tower in the Pyrenees, during a winter thunderstorm occurred in the night of the 6 January 2018.

II. DATA

A. *"Eagle Nest" Instrumented Tower*

The Eagle Nest Tower (hereafter, ENT) is located in Tosa d'Alp (2,537 m asl) in the eastern part of the Pyrenees (Fig.1). It is one of the few instrumented towers around Europe (along with Gaisberg in Austria, Säntis in Switzerland and Peissenberg in Germany). Since 2011 the tower is instrumented to measure direct lightning strikes, see details in [2]. It is worth noticing that the ENT is a peculiar installation, since it is the smallest of the instrumented towers around the world (25 m), but, at the same time, the one at the highest peak (2,537 m asl) (Fig.1)

B. *Auxiliary instrumentation*

There are other instruments in the vicinity that complement the measurements of lightning at the ENT. On the one hand, a 3D stand-alone narrowband VHF interferometer (hereafter, 3D-INT) was installed on October 2011 at Das (1,235 m asl) a few kilometres of the Tower. Such data allows mapping the leader channels emerging from the ENT. More details on this particular equipment can be found in [2].

On the other hand, a Micro Rain Radar (MRR) installed near Das (1,100 m asl, four km away from the ENT) provides precipitation profile observations. The MRR is a Doppler radar vertical profiler operating at 24 GHz ([18-19]) and was configured to derive 1 min averaged vertical profiles of 3 km above ground level estimates of radar reflectivity, spectral width and Doppler vertical velocity. Data was post-processed using the methodology proposed by [20] which is especially suited for winter precipitations.

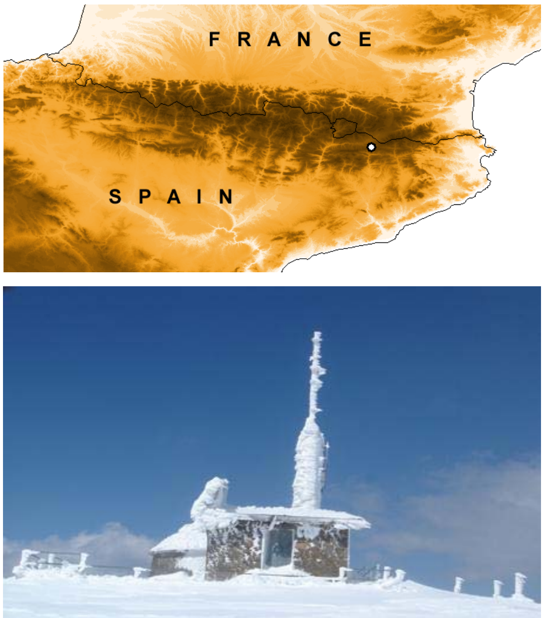

Fig. 1. The Eagle Nest Tower is located in Tosa d'Alp (2,537 m asl) in the eastern part of the Pyrenees (white dot in upper panel).

In addition, an automatic weather station (AWS) managed by the Meteorological Service of Catalonia (SMC) measures wind and temperature 400 m west of the ENT.

Finally, the ENT area is in the area of coverage of long-range meteorological observation systems like the C-band radar network and the lightning location system (LLS) of the SMC. For details see [21-22]. Additionally, lightning data from the European LINET LLS [23] has also been used in the analysis.

III. OVERVIEW OF THE CASE STUDY

On the night of 6th to 7th January 2018 a cut-of-low over the Iberian Peninsula with a jet stream exit located over the Balearic islands produced a sharp difluence at high-levels over NE Spain while at mid-levels, the low with a cold air core with values of –32°C at 500 hPa (Fig. 2) produced a considerable advection of cyclonic vorticity. South of the Pyrenees a surface low with several frontal bands favoured an easterly moist and mild flow on the boundary layer which contrasted with the colder air above it at 875 hPa. The convergence of two low-level jets from south and east at 925 hPa over the study area produced low-level updrafts that could have been supported at mid and high levels by the ageostrophic circulations at the left side of the exit area of the jet stream.

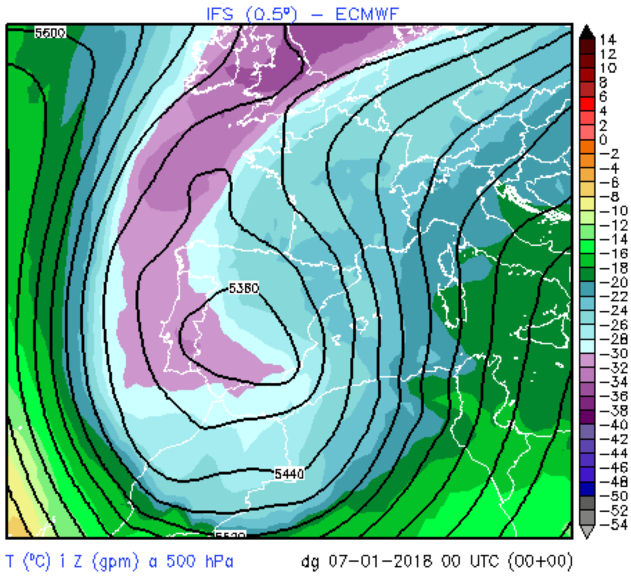

Fig. 2. Meteorological analysis at 00Z 7th January 2018 showing 500 hPa geopotential height contours (gpm) and temperature (shaded, °C). Source: European Centre for Medium-Range Weather Forecasts (ECMWF) model.

IV. RESULTS AND DISCUSSION

A. Lightning

The convective system that finally affected the ENT area (see details in the radar section), had successive enhancements in the lighting flash rate (Fig.3), reaching a maximum of 14 IC flash min^{-1}. The CG flash rate was more constant, staying around 2-3 CG min^{-1}. At the time of crossing the ENT area, the flash rate had decreased to lower values, both in the IC and CG fraction (Fig.3).

Three return strokes were measured at the ENT at 23:06:57 UTC. Fig.4 shows the current waveform measured at the instrumented Tower. The LINET network detected three CG strokes at the tower (location accuracy between 250-300 m) while the SMC-LLS only reported one CG stroke. Besides, SMC-LLS measured VHF sources corresponding to IC channels few milliseconds before the CG strokes at the ENT. Records from both LLS are depicted in Table I. It is noticeable that CG lightning activity at the tower was isolated, with no other CGs in the vicinity.

Records from the 3D-INT, plotted in Fig.5, show VHF bursts above the Tower. It is worth noticing that the 3D-INT resolves azimuth and elevation for each VHF source. Therefore, in order to account only for the activity linked to the ENT, data presented in Fig.5 was previously delimited to an azimuth range around the ENT. Interestingly, VHF sources plotted in Fig.5 were collocated with the SMC-LLS and LINET detections (Table I). These time correspondences bring evidence on the involvement of the ENT in such events. The IC detected by the SMC-LLS at 23:06:57.752 UTC seems to correspond to a short upward leader, since the elevation measurements from the 3D-INT situate the VHF sources around the Tower tip, but not developing any further (in height). The next detections by the 3D-INT at the ENT suggest there was another upward channel at 23:06:57.770 UTC, this time with response at the Tower (Fig.4) and in LINET as a CG stroke. Afterwards came two other CG strokes in LINET (23:06:57.785 and 23:06:57.812 UTC), the last one being recorded also by the SMC-LLS (Table I).

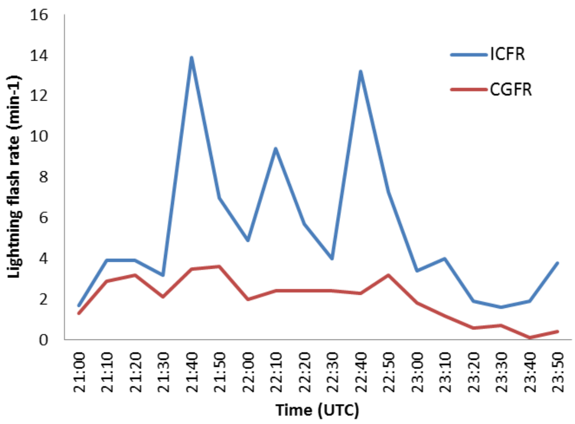

Fig. 3. Intra-cloud (IC) and cloud-to-ground (CG) flash rate (min^{-1}) for the thunderstorm structure that affected the area of study

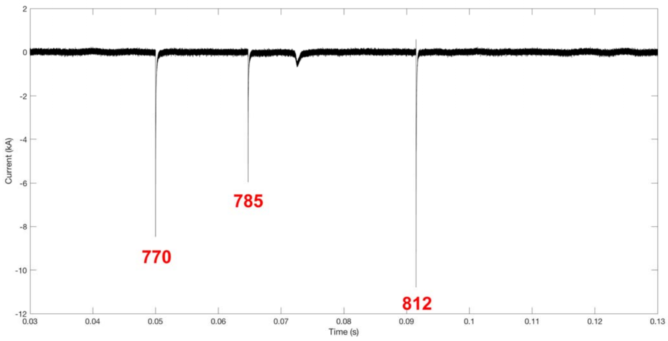

Fig. 4. Current waveform measured at the Eagle Nest Tower at 23:06:57 UTC.

TABLE I. LIGHTNING RECORDS OF SMC-LLS AND LINET RELATED TO THE LIGHTNING AT THE TOWER AT 23:06:57 UTC

Time	Lightning Location System Records			
	SMC-LLS		*LINET*	
23:06:57	0.752	IC		
23:06:57			0.770	CG (-7.5)
23:06:57			0.785	CG (-5.3)
23:06:57	0.812	CG (-13.2)	0.812	CG (-10.0)

All in all, 3D-INT observations (Fig.5) of upward leaders suggest that the three CG strokes detected by LINET were triggered by the ENT. Such CG strokes would have lowered negative charges to the ground, which in turn were initiated by upward positive leaders from the tower tip, propagating toward the charged cloud.

Regarding the type of UL, there was no evidence of a triggering effect by another flash in the vicinity, since the last activity before the ENT event was an IC flash detected by the SMC-LLS 5 seconds before (23:06:51 UTC), 5 km away from the ENT. LINET records around the ENT were isolated, suggesting also the analyzed envent was a SIUL.

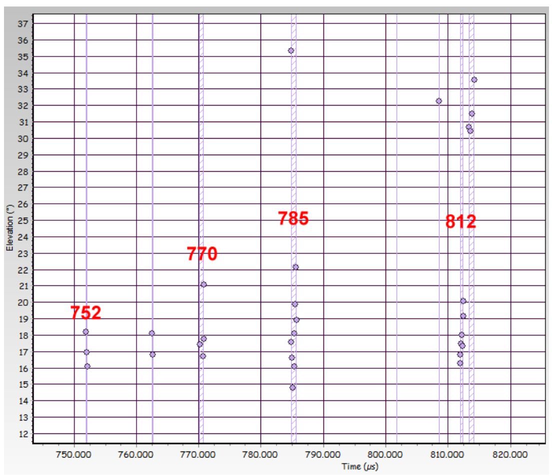

Fig. 5. Sources by 3D stand-alone VHF interferometer for the 23:06:57 UTC event, elevation vs. time. Data was previously delimited to the Eagle Nest Tower azimuth.

B. *Radar*

Given the evidence of upward lightning from the ENT, related meteorological conditions are analysed in the following. First, C-band radar imagery from the SMC was analysed. The MAX product sequence shows a stratiform cloud system of relatively weak echo intensity (10-25 dBZ) with embedded convective cores (25-40 dBZ) crossing above the ENT from South to North. A vertical cross section on the radar volume at 23:06 UTC (Fig.6) shows low cloud top heights on the stratiform part (5-6 km) and embedded convective cores on the left reaching 8 km asl. This stronger echo region shown in Fig.6 was around ten km west of the ENT when the tower initiated the upwards. SMC-LLS records confirm IC cloud activity on that core (not shown). However, activity at the Tower was isolated, with stratiform clouds above.

Evidence of lightning at the ENT leads us to think in an effective charge transfer from the active convection area to the neighbouring stratiform region (Fig.6), favouring the electric field enhancement above the tower and the efficient charge accumulation in the stratiform cloud, enough to support UL. According to Yuan et al. [24] while the charge transferred from the active convection area may had facilitated the efficient charge accumulation in the stratiform cloud, the low cloud top height may also be vital for the initiation of the upwards.

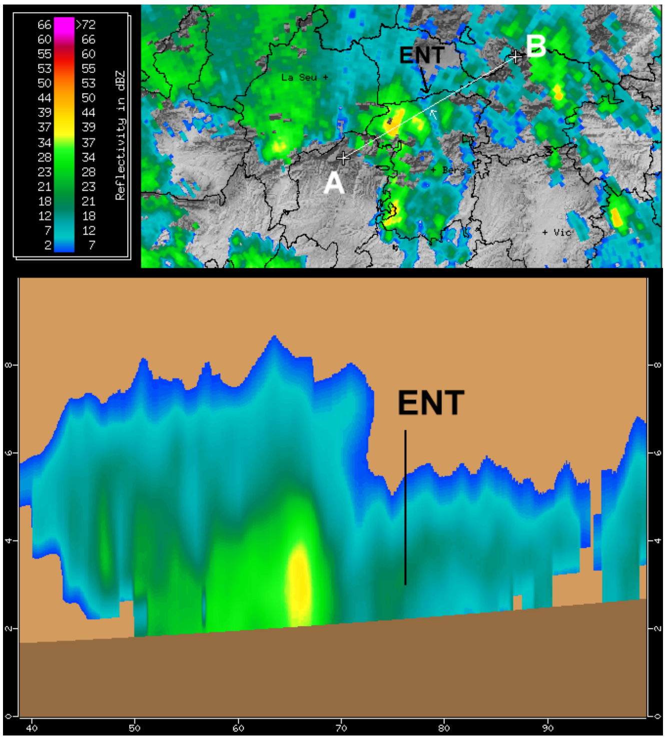

Fig. 6. Plain projection (top) and vertical cross section (bottom) on the radar volume at 23:06 UTC. Radar reflectivities are expressed in dBZ. The cross section segment is indicated by the letters A and B in the top panel.

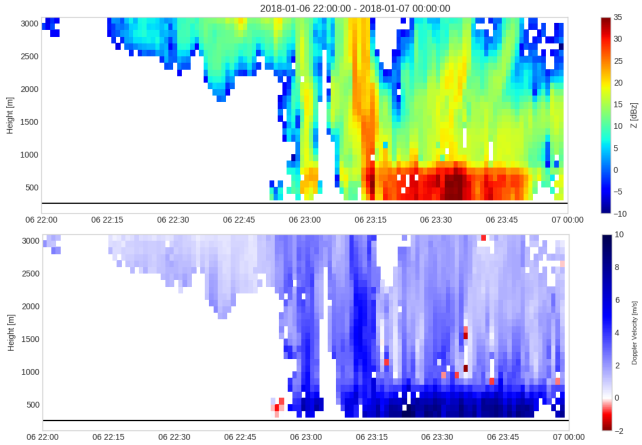

Fig. 7. Micro Rain Radar profiles from 2018/01/06 22:00 UTC to 2018/01/07 00:00 UTC reflecitivity (top panel) and fall speed (bottom panel)

MRR observations (Fig. 7) indicate the presence of convective precipitation from 23:10 to 23:15 UTC, with reflectivities above the bright band exceeding 20 dBZ, evolving later (23:15 to 23:45 UTC) to stratiform precipitation. During the stratiform stage an abrupt change at 1000 m in the reflectivity and fall speed (Fig. 7) profiles suggests the effect of the freezing level.

This setting would be consistent with the C-band observations discussed earlier, providing an independent and complementary view of the convective cell (shown both in the MRR data and the C-band observations) which would likely be associated with the lightning activity triggered by the tower.

C. *Wind conditions*

Wang and Takagi [25] pointed out that the wind may play a substantial role in removing the corona-produced screening layer upon the tower tip, facilitating the initiation of UL. This shielding charge will act to inhibit upward leader inception unless wind can effectively remove this layer.

In the present case study, wind records from an AWS located 400 m east of the ENT were available. During the episode, the wind was blowing steadily from SSE. It suddenly increased its speed with the storm arrival, from 10 $m \cdot s^{-1}$ to a maximum of 23 $m \cdot s^{-1}$ at 23:00 UTC.

According to Warner et al. [26], who analysed UL from towers under similar conditions (low cloud bases, low freezing levels, and falling snow), SIULs would only launch from the towers under winds stronger than 8 $m \cdot s^{-1}$ near the tower top, suggesting that strong ambient winds can effectively remove the shielding to allow for leader initiation.

D. *Height of significant temperatures from NWP soundings*

Shindo et al. [27] found that UL tend to occur when the altitude of –10°C is below 6 km. Relying on the graupel–ice mechanism model to explain cloud electrification [28-29], temperature profiles are indicative of the height of electrical charge centres [30]. In this regard, significant environmental temperatures are the –10° and –40°C, which delimit the mixed-phase region, where the charged regions reside. There is also a strong correlation between lightning initiation and strong radar echoes between the –10° and –20°C levels (e.g. [31-32]). Moreover, studies on winter lightning (e.g. [33-34]) have found that these environmental temperatures also apply to winter storms, despite being at rather low altitudes.

In this regard, temperature records from the nearby AWS indicated that the ENT was around –2.5ºC at 23:00 UTC. On the other hand, we used NWP derived temperature profiles (2018/01/07 00:00 UTC) to infer the height of significant temperatures. The -10ºC was at 3,500 m asl (fulfilling Shindo's condition), while the –20ºC was around 5,000 m asl, which is indicative of the height of the main negative charge region. Such low charge centre is vital for the initiation of upward leaders from high structures [24].

V. FINAL REMARKS

A winter thundercloud crossing the Pyrenees, exhibiting low cloud tops and a low charge centre, triggered upward lightning from the Eagle Nest Tower. Although the convective core was 10 km away from the ENT, the environment electric field on the stratified cloud above the Tower was sufficient for the triggering of upward leaders and subsequent negative CG lightning. Conditions for the upward inception may have been slowly built-up by the cloud electrification, or abruptly enhanced by nearby lightning cloud channels.

Our findings agree with previous studies (e.g. [24], [26], [27]), where upward lightning from towers were initiated in the stratiform region of a stormy system with low cloud top heights, low charge centres and overall low lightning frequency.

While the general principles of lightning protection apply to all objects and systems, tall structures with sufficient height deserve special attention as they have a higher probability of being affected by lightning, especially by upwards. As Rachidi et al. [1] pointed out, neglecting upward flashes, as done nowadays in risk assessment, might result in an important underestimation of the actual number of strikes to tall structures. The present results provide new evidence supporting this statement, as lightning pose a threat to towers during winter low-intensity thunderstorms. Winter lightning are not a significant contribution to the lightning climatology of the region, in terms of the amount of lightning and therefore the region's average flash density, which is the main lightning parameter used in risk assessment.

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